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PRODUCTION STRATEGIES FOR PRODUCTION-QUALITY PARTS FOR AEROSPACE APPLICATIONS

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ABSTRACT

A combination of rapid prototyping processes (3D Systems' stereolithography and Sanders Prototyping's ModelMaker) are combined with gelcasting to produce high quality silicon nitride components that were performance tested under simulated use conditions. Two types of aerospace components were produced, a low-force rocket thruster and a simulated airfoil section. The rocket was tested in a test stand using varying mixtures of H_2 and O_2, whereas the simulated airfoil was tested by subjecting it to a 0.3 Mach jet-fuel burner flame. Both parts performed successfully, demonstrating the usefulness of the rapid prototyping in efforts to effect materials substitution. In addition, the simulated airfoil was used to explore the possibility of applying thermal/environmental barrier coatings and providing for internal cooling of ceramic parts. It is concluded that this strategy for processing offers the ceramic engineer all the flexibility normally associated with investment casting of superalloys.

INTRODUCTION

Research on the production of fully-functional parts by rapid prototyping, or solid freeform fabrication, can be pursued via two complementary approaches; direct or indirect fabrication. The direct approach involves layer-wise construction in the material of choice. In contrast, indirect fabrication typically employs RP processes to produce a shaped cavity that allows a secondary operation, such as casting or injection molding, to produce the part. Depending on the constraints associated with a particular set of circumstances, either approach can be valid. The indirect approach can be advantageous if it is desired to ultimately transition to a more conventional manufacturing procedure once the prototyping phase is complete. Such was the case for the work reported herein.

The two components that were selected for evaluation are a low-force rocket thruster and a simulated-airfoil test specimen. These two parts are representative of anticipated aerospace applications for ceramics.

Rocket engines and gas turbine engines operate on fundamentally different principles. A rocket, in its conventional form, is an internal-combustion engine that needs no outside air to operate. It carries both fuel and oxidizer, which are burned together in a combustion chamber and produce hot gases that are discharged through a

nozzle. The resultant imbalance of forces in the chamber results in propulsion. In contrast, a gas turbine engine necessary contains rotating machinery elements and relies on the ingestion of air to oxidize the fuel. Despite such differences, components for the two types of application have much in common from the point of view of material property requirements and complexity of design,

In particular, both types of propulsion systems have readily identifiable material challenges. Of particular interest with regards to engineering ceramic, is the thermal loads applied to dimensionally critical parts such as the injector nozzle for rocket engines and the first stage vanes and nozzles in a gas turbine engines. In both systems, the need for precise thermal management has severely limited the choices of materials. Typically, the solution is to employ materials that can be manufactured such that there are complex interior passages to allow active cooling of certain critical parts.

Currently, nickel-based superalloys dominate the high- temperature materials market for power-generation and aerospace engine applications. Such materials have a rich history and represent a triumph of metallurgical engineering; it is fair to say that the gas turbine engine would not be possible had superalloys not been developed. Efforts to improve the performance of modern gas turbine engines has imposed increasing service temperature demands on structural materials. In this context, it is important to recognize that "superalloys are utilized at a higher fraction of their actual melting point than any other class of broadly commercial material" [Sims, 1984]. Cleverly designed cooling systems have extended the range of service, but the margins for further improvement appear modest and attention has turned to materials substitution. In particular, covalently bonded ceramic materials, such as silicon carbide and silicon nitride, have received a great deal of attention. Ceramics offer improved refractoriness and have the additional benefit of lower density (of particular relevance to rotating components). Low fracture toughness and high processing costs have proven to be the major obstacle to their widespread application.

The issue of fracture toughness has been addressed using two different approaches, fiber-reinforcement of composites [Chiang et al., 1993; Evans, 1990] and the development of in-situ toughening based on microstructural design [Evans, 1990; Li and Yamanis, 1989; Khandelwal et al., 1995; Sajgalik et al., 1995]. In particular, the development of high-toughness silicon nitride has proven remarkably successful and it will be used as a reference point in this discussion as well as the baseline material in the proposed research project. Materials are available that are both tough and strong, and that maintain their desirable properties to high temperatures. There are a number of commercial sources of in-situ toughened silicon nitride with K_{IC} of around 7-8 MPa$\sqrt{m}$ and four-point bending strength of 700-800 MPa. Two fundamental questions arise: Can an arbitrary desired geometry be readily obtained using a process?, and What is the cost associated with such a process? These two questions apply equally well to applications in rocket and gas turbine engines. The later will be discussed first.

The issue of high processing costs is important in several contexts. Firstly, the production of silicon nitride is a powder-based process. Typically, the storage of geometrical information (shaping) is carried out in a separate unit operation from that used to develop the microstructure (firing) with the powder processes used in the fabrication of ceramic components. Thus, tooling must be specifically designed to accommodate any dimensional changes that are encountered during subsequent

densification. Iterative redesign, or simple modification, of tooling can be prohibitively expensive. Post densification machining of ceramics also is expensive [Anon., 1993]. This is particularly true when high value-added ceramics are used. To a certain extent, green machining can be used to bring a piece into tolerance before firing [Teeter, 1966; Butler et al., 1990], but there is a fundamental limitation associated with all machining approaches; they are restricted to removal of material from the external surface (and boring of holes of simple geometry). This limitation is particularly severe for the opportunity discussed below.

Cooled metallic components for both rocket and turbine applications typically have internal passages through which bypass air is circulated. The geometries are usually complex; features are included to induce turbulence and to control the relative flux of cooling air to different parts of the blade or vane. The complex interior surface is almost always produced by a "coring" technology coupled to a sophisticated investment casting process; for most applications, it cannot be produced by machining [Clegg, 1991].

The use of (ceramic) cores in investment casting is a complex process. The most commonly used core system is based on silica. As-fabricated cores are porous vitreous silica of relatively coarse particle size. The core is used in combination with a shell (also typically silica-based). During investment the hot metal is shaped by both the shell (which defines the external surface) and the core (which defines the internal surface). The heat available from the metal during solidification causes the silica to devitrify, i.e., it crystallizes to form the polymorph cristobalite. During subsequent cooling, the displacive phase transformation which occurs at roughly 200 to 250¡C causes the core to breakup and become a loose powder. Crushing is promoted by the thermal contraction of the metal. At room temperature, the core is removed by a combination of chemical etching and flushing. A few core systems are available that do not employ silica, but they are typically very difficult to remove. To summarize, a core has to be sufficiently strong to shape the persistent material and, when this process is complete, lose its strength completely.

Coring in a powder-based process is problematic because, in general, the persistent material cannot be used to convert the state of a core nor does the powder compact have sufficient strength to crush the core. Early efforts at replacing metallic components with ceramics assumed that the ceramic components would operate uncooled [e.g., Devendra, 1990]. In part, this was motivated by a desire to increase efficiency by reducing the parasitic use of cooling air, but a larger issue is simply the manufacture of such a component as there is no equivalent to a coring technology for powder based processing. (Furthermore, there has been concern that both the steady state and transient thermal stresses associated with the internally-cooled ceramic hardware would be unsustainable.)

The alternative to coring-casting is to machine a large number of small parts and use a complex assembly to produce the required functionality. Although widely used, particularly in rocketry applications, such systems are inherently far less reliable and much more costly that "monolithic" parts.

Thus, both the issues of manufacturability and the cost of manufacturing have become important issues in the potential application of engineering ceramics in gas turbines. The objective of this work was to evaluate the use of a combination of RP

processes to produce cores and molds that could be used to produce parts typical of the intended field of application.

DESCRIPTION OF COMPONENTS AND MATERIALS

The first component selected was a 25lbf rocket thruster designed by researchers at the NASA Glenn Research Center, which can be evaluated using an existing rocket test stand. Key geometrical features are: a 37° flare fitting used to attach the chamber to the injector body on the test stand; a cylindrical combustion chamber; and a converging-diverging throat section leading to a conical exit. The entire part is a body of revolution.

The second component was a simulated airfoil test sample that was equivalent to the specimens used by NASA engineers in their original work to develop thermal barrier coatings for superalloys. Original castings were reverse engineered to obtain the design. The specimen has a geometry that is intentionally simplified. The section to be exposed to the flame during testing is a teardrop shaped; the cross section has two semicircular ends of differing radius joined by flat side. The base of the specimen, used for mounting, is a right circular cylinder. The part is hollow and cooling air can be introduced during testing.

The components were produced from a particular silicon nitride alloy (GS-44, AlliedSignal Ceramic Components, Torrance CA) which was supplied as a spray dried powder. This material was calcined to remove the organic binder prior to use in gelcasting formulations. A plasma-sprayed mullite coating was applied to the surface of one of the simulated airfoils prior to testing.

PROCESS STRATEGY

The process used to create the ceramic parts was gelcasting [Young et al., 1991; Janney et al., 1997; Omatete et al., 1998]. The principal attributes of this process in the context of this work is the ability to do room temperature pressureless casting to form a green ceramic part. As such the process is compatible with the use of polymeric molds and cores. The cast slurry solidifies by gelation; the carrier fluid in the ceramic slurry is actually an unstable aqueous solution of a monomer that is catalyzed immediately prior to mold filling. The resultant wet gelled parts were dried and fired following standard ceramic processes [Reed, 1995].

Molds were produced using stereolithography using a 3D Systems 250/40 machine with Ciba Geigy 5170 acrylate/epoxy resin. The cores were produced on a Sanders Protoyping ModelMaker using ProtoBuild™. As ProtoBuild is soluble in room temperature alcohols, cores were removed by submersing the wet gelled parts in vat of ethanol.

RESULTS

The strategy to produce the rocket thrustor was to design a six-part mold that included a pullable two-part core, a two-part split mold, a baseplate, and an core-mold alignment fixture, see Fig. 1. Using molds of this type, parts were cast from plaster-of-Paris (to ensure functionality of the system), aluminum oxide (to demonstrate technology with a relatively low cost engineering ceramic), and silicon nitride (to produce testable parts).

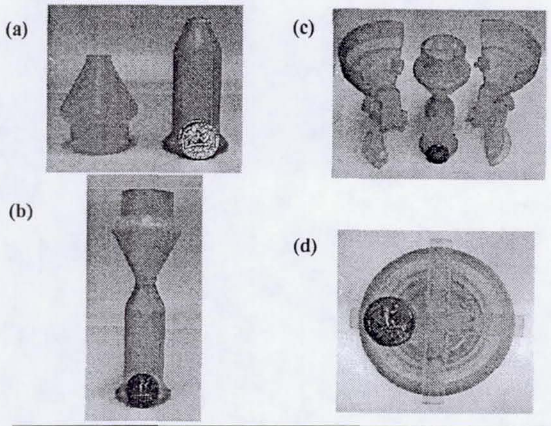


Fig. 1 Mold/core set to produce NASA rocket, produced in epoxy/acrylate by stereolithgraphy.

Green and fired silicon nitride parts are shown in Fig. 2. Figure 3 shows the silicon nitride rocket thruster during testing at NASA Glenn. Significant features of the test are: i) standard mounting using a 37° flare fitting was demonstrated (no need to redesign particular to ceramic); ii) durability of the ceramic part was satisfactory (a series of firings of increasing duration, up to 5 mins., were carried out with no failure); significant thermal gradients are present in the part (estimated at up to 1000°C/mm in the throat). Clearly high quality parts are produced via this strategy.

The excitement regarding this strategy is in part the ability to produce useful parts and as importantly the ability to produce them rapidly; the total elapsed time between idea and ceramic part was 28 days (19 work days). This was for all steps from CAD to RP to ceramic processing. This creates a situation wherein it is possible to rapidly evaluate potential for performance, prior to committing to a systematic and exhaustive experimental plan to optimize component design.

A similar strategy was employed to produce the simulate-airfoil test specimen. A green part are presented in Fig. 4, specimens during testing are shown in Fig. 5, and post-test surface condition is documented in Fig 6. In this case, all parts exhibited adequate thermal shock resistance.

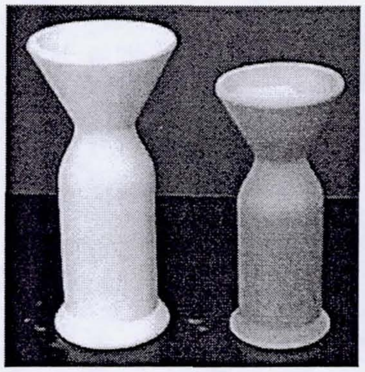


Fig. 2 Green (left) and fired (right) gelcast silcion nitride rocket thrusters.

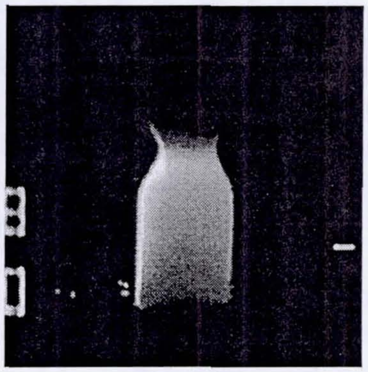


Fig. 3 Silicon nitride rocket thruster during testing in the H_2/O_2 test stand.

However, there was some corrosion of the leading edge of the uncoated specimen. The specimen with the plasma sprayed coating showed no visible signs of degradation despite being subjected to burner for approximately one-half hour. The sequence of photos in Fig. 5 shows the effectiveness of internal cooling in a silicon nitride component. This is further documented in the measurements of surface temperature using pyrometric (both laser and two-color) of the surface temperature on the leading edge of the specimen under the flame, as presented in Fig. 7.

The first of these two specimens (the rocket thruster) clearly indicates a need for sophisticated thermal management. The second (the simulated-airfoil) demonstrates that the approaches, which have been so successfully exploited for metallic components, internal cooling and thermal barrier coatings, both can be effective for ceramic parts. The

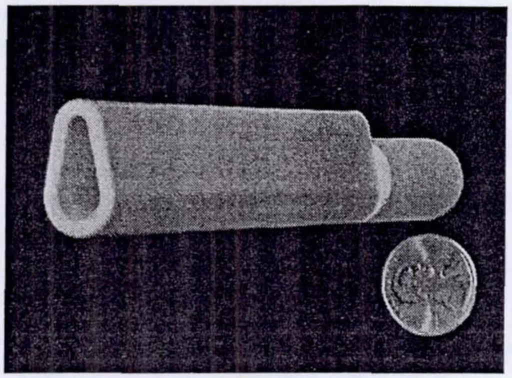
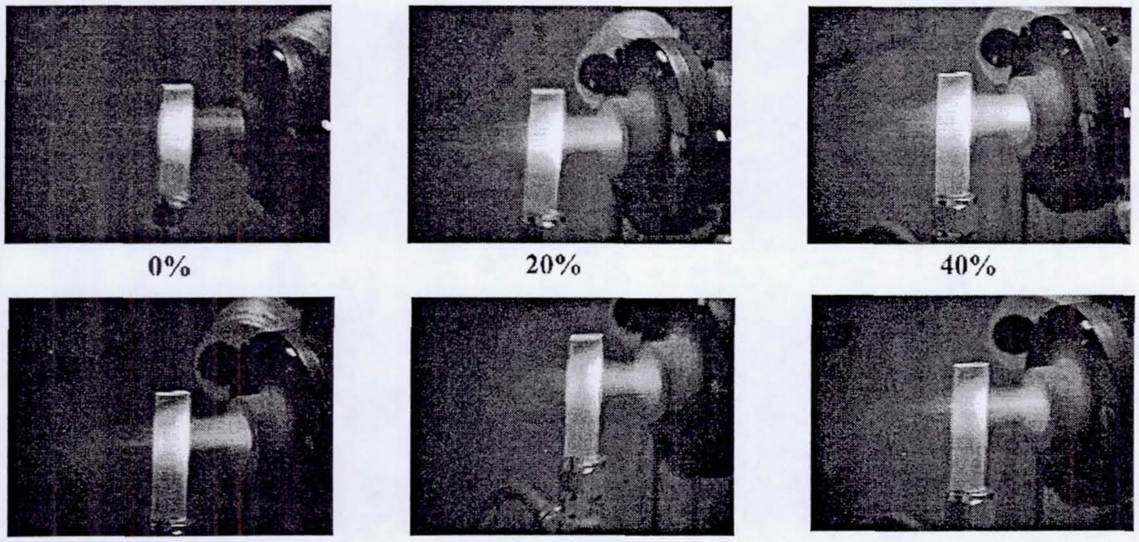


Fig. 4 Green gelcast simulated airfoil.

combination of these results motivated a series of experiments to evaluate the potential for producing more complex internal cooling passages using soluble cores.

Figure 8 shows the assembly of a ProtoBuild core in a epoxy/acrylate mold designed to produce a thin walled (40 mils, or 1 mm) hollow cylinder with thin (13 mil, of 600μm) cooling channels that run the length of the part. The fired part is shown in Fig. 9. This demonstrates the ability to produce precise and finely detailed internal features.



0% **20%** **40%**

60% **80%** **100%**

Fig. 5 Photographs of the uncoated silicon nitride simulated-airfoil test specimen in a Mach 0.3 jet fuel burner flame with differing percentages of 89.8 standard liters of internal cooling air flow. The effect of the cooling air can be seen in the reduction of the intensity of the brightness of the specimen.

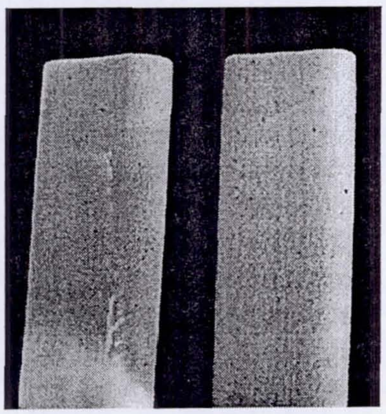


Fig. 6 Surfaces of uncoated and mullite-coated samples after testing.

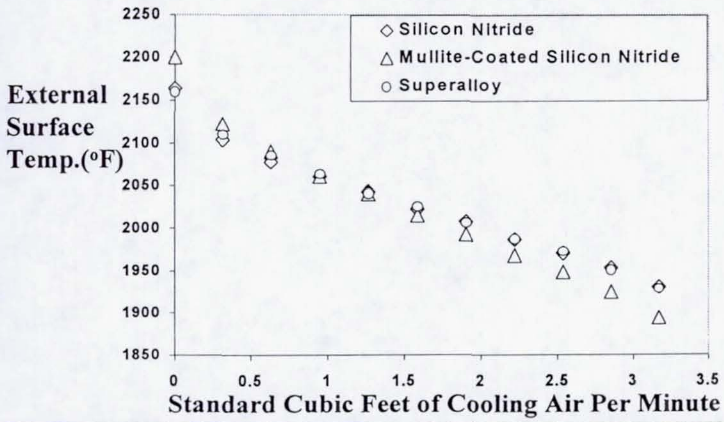
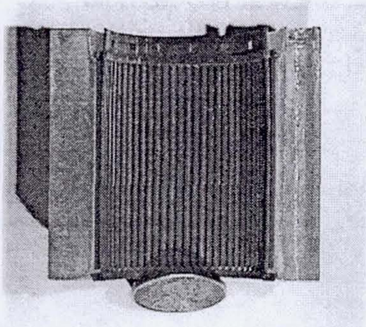
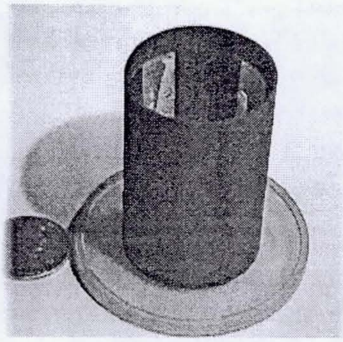


Fig. 7 Graphical depiction of the drop in surface temperature with increasing flow rate of internal cooling air for silicon nitride and superalloy specimens tested under similar conditions.

Actual Cylinder Mold System



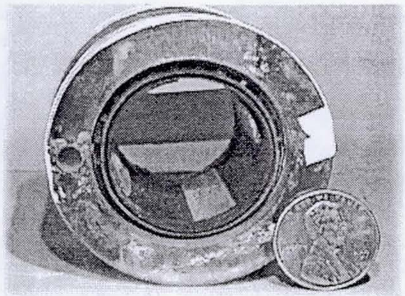
Outer Gating with
Lining and Core Half



Inner Gating with Lining

Fig. 8 Photographs showing the assembly of a core (dark contrast) and mold (light contrast) system used to make a thin walled hollow cylinder with closely-spaced narrow cooling channels that run its length. In order to facilitate removal from the mold, soluble liners were used to separate the part from the mold (a similar design was used to make the simulated-airfoil shown in Fig. 4).

Half Assembled Mold



Full Assembled Mold

Fig. 9 Photograph of fired silicon nitride hollow cylinder with cooling channels.

SUMMARY

The results of the experiments suggest that all of the flexibility normalized associated with cast superalloy aerospace components, complex internal geometrical features produced by coring and ready application of surface coatings, are available to the ceramic engineer. Rapid prototyping has played a key role in allowing this demonstration in a rapid and cost effective manner. Finally, it is noted transitioning this approach to more conventional means is easy to envision, i.e., machined metal tooling of high durability and injection molded cores produced from the appropriate soluble organic.

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